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OF
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TECHNICAL REPORT NO. T34-87

EVALUATION OF A COOLING HEADPIECE DURING WORK IN A HOT ENVIRONMENT

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Abstract

The purpose of this investigation was to evaluate the effectiveness of a new, self-contained cooling headpiece (CHP) in reducing environmental heat stress. The CHP was designed to be worn by the soldier working under thermally stressful conditions, and requires no auxiliary sources of cool air or water. Two male subjects underwent 30 minutes of strenuous cycling on a bicycle ergometer in a climatic chamber at 104° F (40° C). Three trials were conducted on consecutive days: no CHP was worn on day 1, a warm CHP was worn on day 2, and a cold CHP was worn on day 3. The CHP was applied immediately before exercise and was worn for the entire 30 minute period. The cold CHP significantly reduced rate of esophageal temperature rise (ΔTes), heart rate (HR), heat strain index (SI) and heat storage (HS) in both subjects. No differences were observed in sweat rate (SR) or mean weighted skin temperature (MWST). The CHP minimizes the physiological strain of working in a hot environment by removing a significant amount of heat from the scalp and face. Although the device has several advantages - it is untethered, re-useable and inexpensive to manufacture - limitations were noted. We conclude that the CHP has the potential to reduce the risk of hyperthermia in several military situations of short duration, and shows promise for further research and development.

INTRODUCTION

This investigation was conducted to evaluate the effectiveness of a self-contained cooling headpiece (CHP) in reducing environmental heat stress. The CHP was developed at the Aerospace Medical Research Laboratory, Wright Patterson AFB to be worn by the soldier working in a thermally stressful environment. After preliminary testing of the device at Wright Patterson and Brooks AFB, the Heat Research Division, USARIEM was informed of potential body cooling applications. This pilot study attempted to provide a scientific basis for these anecdotal accounts and to evaluate the potential for further development of the CHP. COL Mary Foley of the USAFR collaborated with the Heat Research Division while on reserve duty, and due to time constraints, testing was limited to only two subjects. Trends indicated that the CHP may prevent heat illness by removing heat from the body.

The benefits of cooling the scalp and face are well known. Ventilated helmets, water-cooled helmet liners and cooling caps have been successful in reducing core temperature, heat storage, heat strain, heart rate, and discomfort in exercising subjects and sedentary subjects in full gear (Shvartz, 1970; Williams, 1974; Kissen, 1976; Brown, 1982; Nunnelly, 1982). The CHP is unique in that it is untethered and requires no auxiliary sources of cool air or water. The CHP enables the soldier to work in a hot environment unrestrained, with a minimal risk of hyperthermia. This cooling headpiece would be valuable in many situations where whole body cooling suits are impractical.

It has been demonstrated that head cooling may be equivalent to cooling 60% of the torso excluding the head, in subjects undergoing moderate exercise at 122° F (50° C) (Shvartz, 1970). In testing several water-cooled suits under various environmental conditions, Shvartz determined that a water-cooled hood reduced heat strain by one-third (Shvartz, 1972). Nunnelly observed that a water-cooled cap removed 19% of heat produced in subjects walking at neutral and warm environmental temperatures, and 30% of metabolic heat in subjects resting under the same conditions (Nunnelly, 1971).

Thermoregulatory mechanisms lose their effectiveness with increasing environmental and metabolic heat loads. Core temperature and heart rate increase due to the physiological toll of maintaining homeostasis. The soldier working in warm ambient temperatures may develop heat illness which may either limit physical activity or result in collapse. Heat is dissipated by the evaporation of sweat and by skin blood flow, which increases 90-100% with elevated core temperature during exercise (Armstrong and Dziados, 1986). Superficial veins play an important role in thermoregulation by dilating or constricting in response to core and skin temperature input. Cooling garments reduce heat storage by removing heat from the superficial vasculature.

The head is an extremely efficient area for heat removal. The highest heat flux region of the body other than working muscle (Nunnelly, 1971), the scalp has the highest skin temperatures (Hertzman, 1959). It has been determined that 50% of metabolic heat is lost through the head in a cold environment (Froese, 1957). The rich supply of superficial vasculature and the lack of vasoconstrictive innervation allow substantial heat removal when cool air or water flows over the face and scalp. A countercurrent exchange system has been postulated in which cooled venous blood from facial skin cools arterial blood when core temperature is elevated (Brown, 1982). Head temperature may therefore play a role in whole body thermoregulation by influencing central blood temperature. Although the scalp, face and neck comprise only 7-9% of the total body surface area, cooling the head reduces core temperatures both at rest and during exercise.

Defense of brain temperature has been implicated in the prevention of serious heat illness (Cabanac, 1983). It is estimated that the highest temperature tolerated by the brain is 105.9° F (40.5° C), although rectal temperatures as high as 107.4° F (41.9° C) have been recorded in marathon runners. Many animals including humans have a carotid rete mechanism which selectively cools the brain and protects it from hyperthermia. In addition, cooling the brain improves protection of the hypothalamus, the thermoregulatory center of the body. Fanning the face of heat illness victims has been recommended to cool the blood flowing from facial capillaries to the brain. Head cooling would defend brain temperature by conducting heat from the face and scalp, and may be preventative as well as therapeutic.

MILITARY RELEVANCE

The CHP could be invaluable to the military during hot weather operations, particularly to troops deploying to the tropics, the desert, or other warm areas. A safety precaution in tasks of short duration for unacclimatized individuals, the CHP would also be beneficial under more severe conditions of heat or activity after acclimatization has been achieved. The device would enable firefighters, pilots, airmen, flight line mechanics, and steam fitters to complete their specialized missions with reduced risk of hyperthermia. The CHP could be incorporated into impervious clothing conducive to hyperthermia (G suits, flight suits or MOPP IV for example) and permit the soldier to work unrestrained in a confined space or vehicle such as an aircraft cockpit or personnel carrier.

In addition to physiological benefits, soldier comfort and performance may also be enhanced by the CHP. Scalp temperature may be a factor in whole body thermal comfort (Brown, 1982). Head cooling has been shown to increase subjective comfort ratings (Williams, 1974; Brown, 1982; Nunnelly, 1982) even in one investigation with aircrew members at 140° F (60° C) (Clifford, 1965). One study demonstrated that head cooling reverses reaction time and accuracy decrements in the heat (Nunnelly, 1982). Konz and colleagues have reported that a cooling hood lessened heat strain and improved productivity as measured by a mental task (Konz, 1969). Brouha found that an air-ventilated helmet allowed subjects to perform more work in a hot, moist environment while speeding up recovery from heat stress (Brouha, 1960). The CHP may increase the efficiency of brief work-rest cycles by improving recovery from mild heat stress, and with further development may someday be be used in the treatment of heat illness and heat stroke to lower body temperatures.

STUDY OBJECTIVES

The objectives of this investigation may be summarized as follows:

1. To evaluate the overall effectiveness of the CHP in removing heat from the body and reducing heat stress.
2. To collect preliminary physiological data on exercising subjects in the heat to support anecdotal accounts of CHP effectiveness.

   Three consecutive trials were conducted under the following conditions:

a) Subjects wearing no CHP (control)

b) Subjects wearing a warm CHP

c) Subjects wearing a cold CHP

MATERIALS AND METHODS

Description of CHP

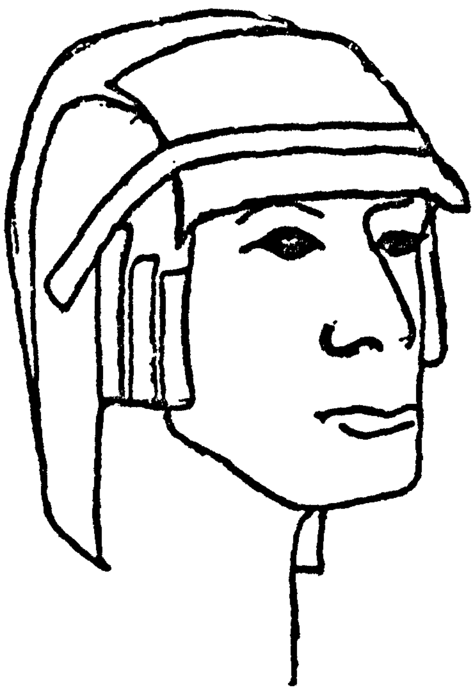
The CHP is illustrated in Fig. 1. A cold pack in the shape of a cavalier helmet, the garment is constructed of a tough vinyl outer shell and inner liner filled with a thick mixture of bentonite clay and glycol. When frozen for several hours before use, the CHP maintains a cold temperature which lasts for some time after removal from the freezer. The CHP weighs 2.5-3 lb and covers approximately 1 square foot, including the scalp, the sides of the face, the ears, and the back of the neck. Placed directly on the head (some type of scalp covering may be worn if the cold sensation is uncomfortable), it is compatible with other gear such as glasses, hard hat helmets and protective clothing. Several safety features are incorporated into the design: it is easily removed, it is difficult to puncture, and in the unlikely event of leakage, the chemical mixture will not readily drip into the eyes or mouth. The CHP requires no power source and is re-freezable. It was developed at the Harry G. Armstrong Aerospace Medical Research Laboratory (AFSC), Wright-Patterson AFB, Ohio, and is manufactured by the Chattanooga Corporation of Chattanooga, Tennessee.

Testing Procedure

Two unacclimatized males from the Heat Research Division served as test subjects. Their descriptive characteristics are as follows: Subject A (age- 27 yr,

FIG. 1

The Cooling Headpiece (CHP)



View 1.

View 2.

View 1: CHP with removeable flap down

View 2: CHP with removeable flap up

height- 184.2 cm, weight- 91.305 kg, surface area- 2.14 m^2); Subject B (age- 46 yr, height- 169.0 cm, weight- 80.350 kg, surface area- 1.91 m^2). Testing was conducted on three consecutive days in the Heat Research Division climatic chamber at 104° F (40° C). Subjects exercised on a Collins Pedalmate bicycle ergometer at 50 rpm for 30 minutes. Subject A warmed up for two minutes at each of the following work levels: 49 W, 98 W, and 147 W. He completed the remaining 24 minutes of exercise at 172 W. Subject B warmed up for two minutes at 49 W and two minutes at 98 W, completeing the remaining 26 minutes of exercise at 110 W. Subjects were working at approximately 85% of their maximum heart rate (HR) as estimated using the age-adjusted maximum heart rate formula (See Appendix A).

Subjects stood for a short equilibration period after entering the chamber and before exercising. During this time they inserted an esophageal probe (Yellow Springs Instruments) to depth of 18 in (46 cm) and were equipped with eight skin thermistors (Yellow Springs Instruments). Mean weighted skin temperature (MWST) was calculated using Equation 2 in Appendix A.
The following protocol was used for the three trials:

Day 1: No CHP was worn.

Day 2: A warm CHP was worn. The CHP was placed in the 104° F climatic chamber to equilibrate with ambient temperature before the trial began.

Day 3: A cold CHP was worn. The headpiece was removed from the freezer immediately before the trial began.

Subjects donned the CHP immediately before exercise. The warm CHP was replaced by a cold CHP approximately 6 minutes after exercise on day 2, to observe any changes in ventilation (Fig. 2 and Fig. 3). On day 3 the CHP was replaced approximately every 15 minutes, once during exercise and once post-exercise as it became warm.

Esophageal temperature (Tes), MWST, and individual skin temperatures were monitored every two minutes with an automated computer system consisting of a Hewlett-Packard 85A computer, scanner and voltmeter. Heart rate was recorded by telemetry (Hewlett-Packard Inc.) on day 1 and by polygraph (Graphtec) on days 2 and 3. Whole body sweat rate (SR) was determined by weighing subjects ±10 g pre-exercise and post-exercise (Sauter balance). Ventilatory parameters were measured on days 2 and 3 by polygraph and pneumotachometer (Hans Rudolph). Expiratory volume ($\dot{V}_E$) and tidal volume ($\dot{V}_T$) were determined post exercise as ratios of steady state values; breathing frequency (f) was also measured. In collaboration with the Heat Research Division, the Cold Research Division obtained a color thermograph of the body during exercise and post-exercise with an Agatherm® camera.

Data Analysis

Mean body temperature (MBT), heat storage (HS), and the Craig heat strain index (SI) were calculated using Equations 3 - 5 in Appendix A. Due to the small sample size in this investigation, statistical procedures were inappropriate for data analysis. It was sufficient to compare data obtained from three trials, as essentially all trends were clear with both subjects.

RESULTS

Core Temperature, Heart Rate, Heat Storage and Heat Strain During Exercise

Thermoregulatory and cardiovascular data for all trials are presented in Table 1. The cold CHP worn on day 3 substantially reduced ΔTes, ΔHR, MBT, HS, and SI during exercise in both subjects. The changes in these parameters were determined to be more descriptive, although final Tes and final HR were also lower on day 3. Subject A had a final Tes of 102.3° F (39.07° C) on both day 1 and day 2, in contrast to 101.2° F (38.41° C) on day 3. Subject B had a final Tes of 101.1° F (38.38° C), 100.7° F (38.16° C) and 99.9° F (37.72° C) on days 1, 2, and 3 respectively. Final HR was 174, 178 and 158 for subject A; subject B had a final HR of 171, 167 and 157. No reductions were observed in ΔMWST or SR.

Skin Temperature

The face and abdomen are strongly weighted in the MWST formula, indicating their importance in thermoregulation by the skin. The lateral neck (used in this study to estimate face temperature) and the abdomen of both subjects were the warmest skin sites on day 1 and day 2. The neck was the coolest site in both subjects on day 3, although the abdomen was still the warmest. The Agatherm® camera revealed cool air flowing from the CHP to the abdomen in both subjects on day 3. The cool air was not completely effective in cooling the whole body skin surface; there were no significant differences in MWST with the cold CHP. Apparently, cooling the scalp and face is sufficient to lower Tes and HS.

Table 1.

Thermoregulatory and Cardiovascular Changes with Head Cooling

Taken at End of 30 Minutes of Exercise

Measurement	Subject	Day 1 No CHP	Day 2 Warm CHP	Day 3 Cold CHP	Percent Change*
Δ Tes (°F)	A	3.08	3.28	2.21	-28
	B	2.16	2.21	1.38	-36
HS (cal/m²/hr)	A	66.909	75.876	56.515	-15
	B	55.099	49.652	33.300	-40
SI (Ia)	A	4.015	4.317	3.475	-13
	B	3.276	3.321	2.751	-16
Δ HR (b/min)	A	100	107	97	- 9
	B	87	81	74	-15
Δ MBT (°F)	A	3.42	3.87	2.86	-16
	B	2.84	2.55	1.73	-39
Δ MHST (°F)	A	4.09	5.06	4.19 +	-
	B	1.58	3.24	1.98	-
Sweat Rate (g/m²)	A	302	335	311	-
	B	192	220	215	-

* From Day 1 to Day 3

\+ Taken at 24 minutes

Comfort

Both subjects reported that they felt more comfortable with head cooling: the heat was more bearable and the exercise was less difficult. Subject A felt an immediate and dramatic cooling when replacing the warm CHP with the cold CHP on day 2 (post-exercise).

Ventilation Post Exercise

Figure 1 and 2 depict the ventilatory parameters for both subjects post-exercise on day 2 and day 3. Data were examined for differences in post-exercise ventilation between days, and for possible effects of the cold CHP applications on day 2 or the cold CHP replacement on day 3. Data were inconclusive since each subject responded differently. In the case of Subject A, post-exercise $\dot{V}_E$, $\dot{V}_T$, and f were lower when wearing the cold CHP (day 3) vs. the warm CHP (day 2), and this difference persisted after application or replacement of the cold CHP until the time of 36 minutes. Subject B had markedly greater decrements in $\dot{V}_E$, $\dot{V}_T$, and f at the end of exercise when wearing the cold CHP. Both application and replacement of the cold CHP lowered $\dot{V}_E$ and f. The immediate changes in ventilation upon cold CHP application or replacement may be a behavioral response rather than a physiological effect of the CHP.

DISCUSSION

The CHP worn on day 3 significantly reduced physiological strain. Both subjects completed 30 minutes of strenuous exercise in the heat with substantial reductions in Tes, HR, HS, MBT, and SI. The CHP permitted simple and effective heat removal for a brief time. In contrast to other successful head

FIG. 2

VENTILATION POST-EXERCISE WITH HEAD COOLING

SUBJECT A

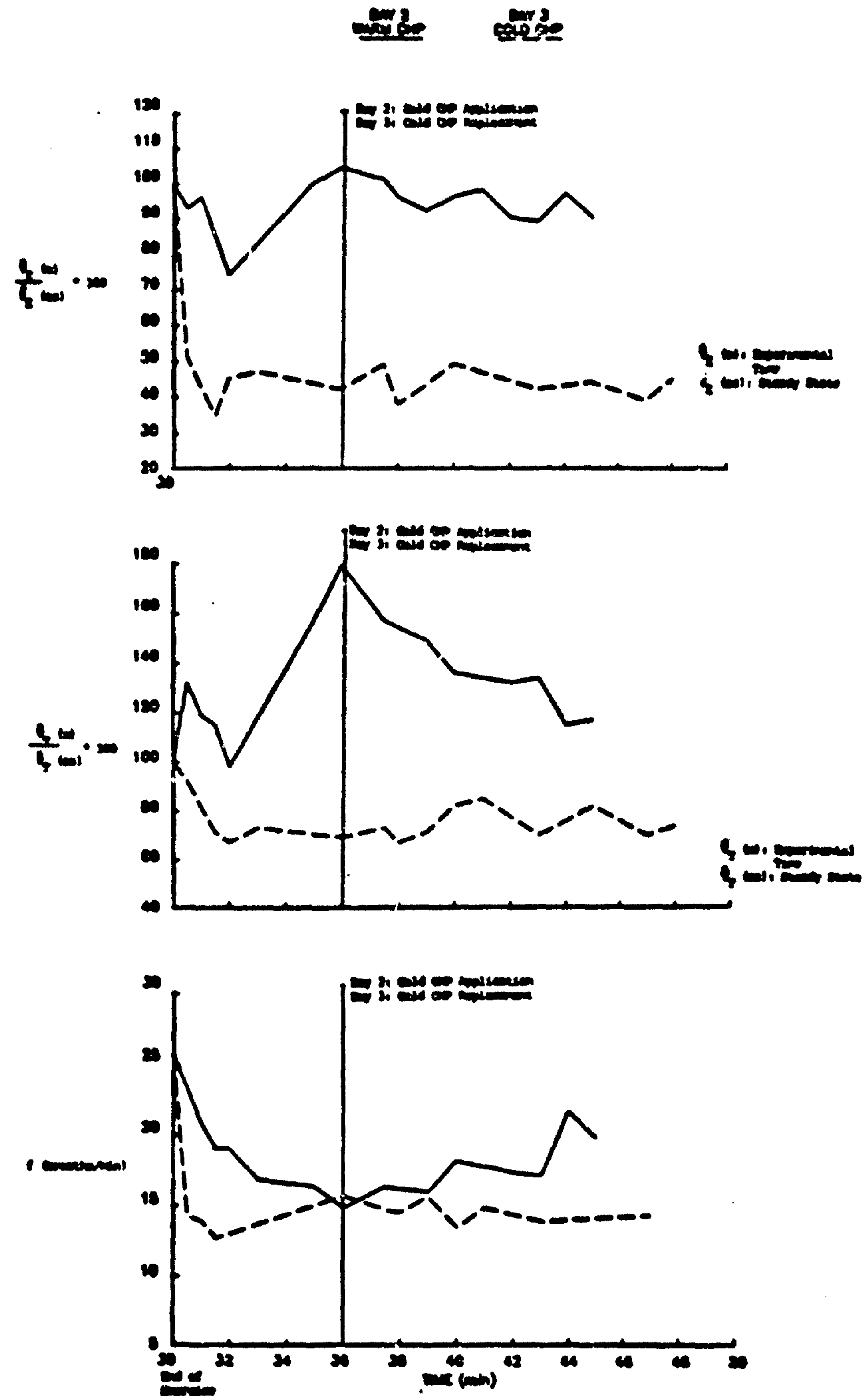
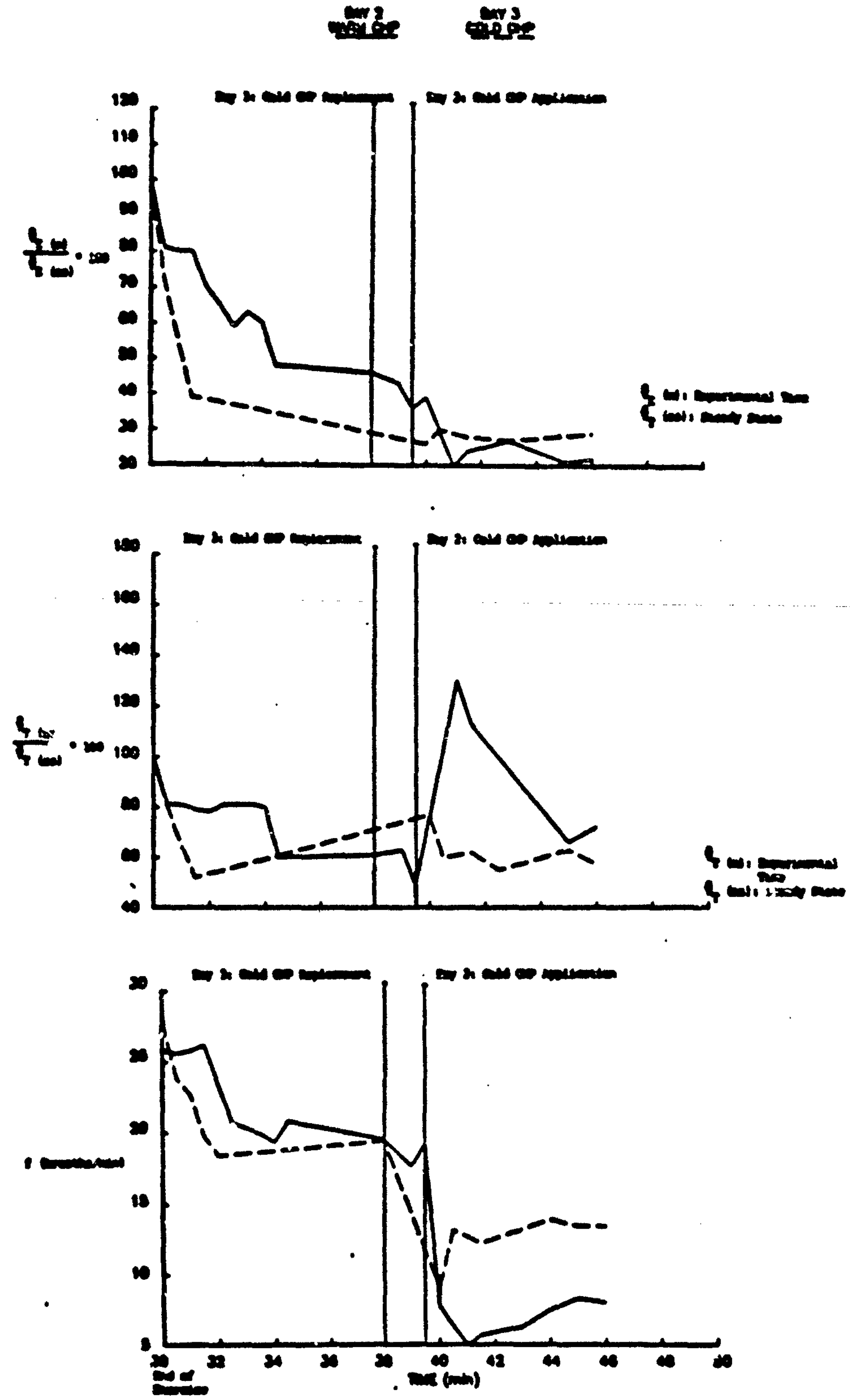


FIG. 3

VENTILATION POST-EXERCISE WITH HEAD COOLING

SUBJECT B



cooling designs, the CHP is self-contained and does not encumber the soldier or interfere with activity. Cooling with the CHP was comparable to cooling with other devices although tested for only 30 minutes and although HS and SI were higher than reported elsewhere (Williams, 1974; Kissen, 1976).

In one study, a liquid-cooled helmet liner incorporated into an Army SPH-4 helicopter aircrew helmet reduced rectal temperature, HR and HS by 50% in subjects dressed in flight suits seated in a 117° F (47° C) chamber (Williams, 1974). Heat strain was reduced from 2.51 Is in uncooled subjects to 1.53 Is in subjects wearing the liner. In a similar study, an air-ventilated Air Force helmet and water-cooled helmet liner reduced heat strain from 2.35 Is to 1.53 Is (Kissen, 1976). Both cooling systems require a hard hat helmet; the latter system requires a remote-controlled air and water supply. The former system not only requires the soldier to carry a source of water but also to control its temperature. Reductions in SI were observed with the CHP in spite of the more strenuous exercise level in this investigation (See Table 2). The CHP can be worn independently, and does not require the installation of an air or water supply into an already crowded vehicle. Moreover, the CHP poses none of the technical complications associated with water cooling. It can easily be worn by the soldier in the field, the soldier in a military vehicle, and the soldier in a confined space or otherwise thermally stressful environment.

Both methods of head cooling, water-cooling the scalp and air-cooling the face, have distinct advantages. Water has a superior heat removal capacity, while the air-cooled face has a better heat transfer potential. As thermography demonstrated, the CHP has the advantage of <u>air cooling</u> by producing a flow of cool air on the face, neck and upper body for heat removal by convection. It has the advantage of water cooling by covering the scalp, neck and parts of the face for heat removal by conduction. Some investigators have expressed the concern that cooling headgear must lie against the scalp for effective heat removal because hair may act as an insulator limiting or delaying heat removal (Nunnelly, 1971; Kissen, 1976; Brown, 1982). The CHP circumvents this problem by covering the entire scalp with a conductive surface, in contrast to hoods constructed from tubing or piping. The benefits of modular or welded headgear have been addressed in other reports. (Williams, 1974; Brown, 1982).

The sweating mechanism is complex and is dependent upon environmental conditions, exercise intensity, body core temperature, and regional skin temperatures. Reduction in sweat rate would be important in preventing body fluid and electrolyte losses during intense exercise or prolonged heat exposure. A lower sweat rate would be important to the soldier in impervious clothing, since sweat which cannot evaporate does not cool the body and body fluid would be lost as "wasted sweat". Also, "wasted sweat" collects in boots and gloves, producing discomfort and complicating movement. Head cooling has been reported to reduce sweat rate in some cases (Nunnelly, 1971; Williams, 1974; Kissen, 1976) and to have no effect in others (Shvartz, 1970). The cold CHP did not reduce sweat rate, however, sweat loss would rarely be a major concern in the time period that a soldier would be wearing the CHP. It seems likely that head cooling must significantly lower core temperature and/or MWST in order to reduce sweat rate.

The cold CHP did not reduce ΔMWST, which is in agreement with several other studies (Shvartz, 1970; Nunnelly, 1971; Williams; 1974; Kissen; 1976). The small area of skin cooled by the CHP was insufficient to reduce sweat rate, but was sufficient to reduce Tes, HS, MBT, SI, HR, and discomfort. Head cooling appears to have an immediate and direct effect on HR and discomfort sensations (Nunnelly, 1971). This observation supports the use of the CHP for short periods of heat exposure; the CHP would enable the soldier to feel comfortable and maintain adequate circulatory balance in spite of an elevated core temperature and skin temperature. The removal of heat from the body would delay further increases in core temperature. The reduced demand for heat dissipation would result in a lower HR and skin blood flow; cardiac output could be maintained.

There are still unanswered questions concerning the CHP and some of the disadvantages must be overcome. For example, the CHP had a tendency to drip condensation as it became warm. The CHP warmed in 15-20 minutes under the conditions used in this study, and therefore is only useful for short periods of time unless replacements are available. The CHP could not be worn with MOPP IV for extended periods since replacement would be involve removing the mask and hood. CHP preparation requires a freezer which would not be available in many military situations. Finally, some soldiers may resist the CHP if they find it causes headaches or other unpleasant sensations. In spite of these negative aspects, the development of the CHP may be a step in the right direction for future body cooling research. In addition to its usefulness in preventing hyperthermia, the CHP may someday be used as a treatment for mild hyperthermia. Data are inconclusive however, and further research is required before a therapeutic value can be assessed.

CONCLUSION

This pilot study demonstrated that the CHP minimized the physiological strain of exercise in the heat by reducing Tes, HS, SI, MBT, and HR. In addition to its efficient body cooling capabilities, the CHP has several advantages: it is light and self-contained, it requires little preparation or maintenance, and is simple to use. Results from this study have significant implications; the soldier wearing the CHP could work in a hot environment unrestrained, with less risk of hyperthermia. Potentially hazardous tasks of short duration could be accomplished, or missions could be prolonged with minimal heat stress and fatigue. In addition to the aforementioned military benefits, applications in industry and athletics are also obvious. The potential of the CHP in treating hyperthermia is promising, but more data is required under a variety of environmental conditions.

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Appendix A

This Appendix lists the equations used to calculate exercise intensity (% max HR), mean weighted skin temperature (MWST), mean body temperature (MBT), heat storage (HS) and Craig Heat Strain Index (SI).

Equation 1 Calculation of age-adjusted maximum heart (Fox, 1971)

Estimated Maximum Heart Rate (b/min) = 220 - age

Equation 2 Calculation of 8 site Mean Weighted Skin Temperature (Nadel, 1977)

Location of Skin Sites
Neck (Tn) [used in place of face (Tf)]
Abdomen (Ta)
Chest (Tch)
Back (Tb)
Thigh (Tt)
Calf (Tca)
Upper Arm (Tu)
Lower Arm (Tl)

$$\text{MWST } (^\circ F) = 0.21\ Tf + 0.17\ Ta + 0.11\ Tch + 0.10\ Tb + 0.15\ Tt + 0.08\ Tca + 0.12\ Tu + 0.06\ Tl$$

Equation 3 Calculation of Mean Body Temperature from core temperature and skin temperature (Craig, 1954).

$$\text{MBT } (^\circ F) = (0.67)\ (\text{Tes}) + (0.33)\ (\text{MWST})$$

Equation 4 Calculation of Heat Storage (Craig, 1954).

BW = Nude Body Weight (kg)
SH = Specific Heat of Body = 0.83
SA = Body Surface Area (m^2)
ΔMBT = Final MBT - Initial MBT ($^\circ$F)

$$\text{HS } (\text{cal/m}^2/\text{hr}) = \frac{(\text{BW})\ (\text{SH})\ (\Delta \text{MBT})}{\text{SA}}$$

Equation 5 Calculation of Craig Heat Strain Index (Craig, 1950).

HR = Heart Rate (b/min)
ΔTes = Esophageal Temperature (° C)
ΔBW = Initial Body Weight - Final Body Weight (kg)

$$SI = \frac{HR}{100} + \Delta Tes + \Delta BW$$

Disclaimers

This investigation was carried out in response to a request from Wright-Patterson Air Force Base to the Commander, USARIEM dated 21 March 1986. The study was conducted in conjunction with a USAF protocol entitled "Use of Head Cooling to Increase Heat Tolerance of Personnel Working in Hot Environments to Facilitate Recovery from Heat Exposure". COL Mary F. Foley, USAF collaborated with the Heat Research Division while on two weeks of reserve active duty training.

The views, opinions, and/or findings contained in this report are those of authors and should not be construed as official Department of the Army position, policy, or decision, unless so designated by other official documentation.

Human subjects participated in these studies after giving their informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 for use of volunteers in research.

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